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A two-dimensional coupled hydro-mechanical finite-discrete model considering porous media flow for simulating hydraulic fracturing

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ABSTRACT

In this study, we propose a new coupled hydro-mechanical model considering porous media flow (FDEM-flow) for simulating hydraulic fracturing, which makes full use of the unique topological connection between joint elements and solid elements in the combined finite-discrete element method (FDEM). The joint elements form the flow channel for fluid, through which flow obeys the cubic law. In addition, viscous forces of fluid are taken into account in FDEM-flow. A simple example with analytical solution is given to verify the model. Then, the effects of fluid viscosity on hydraulic fracturing are investigated by this model. The simulated results show that when a low viscosity fluid is injected, the fluid infiltrates the fracture rapidly. The initiation pressure is lower than the theoretical value and the breakdown pressure is slightly larger than the initiation pressure. When high viscosity fluid is injected, fluid infiltrate into the cracks very slowly. The initiation pressure is close to the theoretical value and the breakdown pressure is much larger than the initiation pressure.

1. Introduction

Hydraulic fracturing is a core technology used in oil and gas wells to increase production, and has been widely used in low-permeability reservoirs and shale gas exploration. It is essentially a rock rupture phenomenon involving hydro-mechanical coupling, which covers a wide range of issues. The study of hydraulic fracturing is of great importance in both theory and practice.

Some hydraulic fracturing models were developed to assist operation design. For example, Perkins and Kern[1] contributed the first model, which was further developed by Nordgren.[2] Geertsma and Klerk[3] developed KGD model. Later, Fung et al.[4] and Cleary et al.[5] proposed some semi-analytical methods to solve hydraulic fracturing problems. Other models include the pseudo-3D (P3D) and planar-3D (PL3D) models.[6,7] More examples of the analytical model can be found in.[8–15]

Although these analytical models are widely used, a common limitation of which is that they can only be used in simulating the propagation of fractures with highly idealised geometries. Therefore, many numerical methods are used to study hydraulic fracturing. These numerical method can be roughly classified into two kinds: (1) continuum-based methods; (2) discontinuum-based methods.

A representative in the continuum-based methods is the seepage-stress-damage coupled model.[16–18] Later, the model was extended to three dimensions by Li et al.,[19] which indicated that the initiation pressure does not coincide with the breakdown pressure. Pan et al.[20] combined rock discontinuum cellular automata with TOUGH code to realise a coupling analysis of solid deformable and fluid flow in fractures. Keshavarzi and Mohammadi,[21] and Chen[22] simulated hydraulic fracturing using an extended finite element method. Wu et al.[23] extends the numerical manifold method (NMM) to include the hydro-mechanical model to simulate crack initiation, propagation, block formation and sliding due to water effect. Xie et al.,[24] Zhang et al.[25] and Zhang et al.[26] used displacement discontinuity method to simulate of hydraulic fracturing and its interactions with a pre-existing fracture. Carrier and Granet,[27] and Chen[28] used finite element method to modelling fluid-driven fracture in permeable medium.

In the discontinuum-based methods, the traditional discrete element method can incorporate joints explicitly. Moreover, the existing commercial codes, such as UDEC[29] or 3DEC,[30] can deal with multi-physics coupling problems. For example, Nasehi et al.[31] investigated with UDEC the effect of *in situ* stresses and strength parameters on hydraulic fracturing. However, these methods cannot directly simulate rock mass fractures, difficulties remain in dealing with those rock fractures driven by fluid.

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To simulate the rupture of rock mass, Cundall[32] proposed the particle flow method (PFC2D, PFC3D), which provides a promising approach to solving rock fracture driven by fluid flow. For example, Al-Busaidi,[33] Zhao,[34] Shimizu,[35] Han,[36] and Wang[37] used the method to study hydraulic fracturing and acoustic emission, and achieved good results. However, the particle flow method has a problem in that the continuum is represented by circular particles bound to each other regardless of how the particles are arranged, the initial model has voids. Therefore, it cannot intuitively characterise the flow paths and crack extension. In addition, the circular particles are rigid, and thus the concept of stress and strain in continuum cannot be directly expressed, but indirectly expressed by statistical averaging with the measurement circle. The stress and strain depend on the radius of the measured circle, the physical meaning of which is not very clear. Ben[38,39] and Jiao et al.[40], and Choo,[41] and Morgan[42] not only considered coupled seepage and stress based on DDA, but also could deal with rock rupture. In addition, Fu et al.[43] proposed an explicilty-coupled hydro-geomechanical model for simulating hydraulic fracturing. Grasselli et al.[44] studied the effect of discontinuity on hydraulic fracturing but without considering fluid flow in the fractures.

Yan et al.[45] based on the combined finite-discrete element method (FDEM) proposed a hydro-mechanical model to simulation of hydraulic fracturing with arbitrarily complex network. In this model, rock matrix is considered to be impervious and pore seepage in rock matrix cannot be considered. However, most reservoir rocks are porous medium through which fluid can flow.[46] The experimental study carried out by Haimson and Fairhurst[47,48] and Medlin and Masse[49] have demonstrated that the porosity and pore fluid have an influence on the hole breakdown pressure. Therefore, in this paper we present a new coupled hydro-mechanical model (FDEM-flow) based on FDEM, which considers both porous media flow and fracture seepage. At the same time, a calibration approach for rock macroscopic permeability is also recommended. Furthermore, we also consider the viscous forces of the fluid.

This paper is organised as follows: first, the basic theory of the coupled hydro-mechanical model considering porous media flow and fracture seepage is introduced; secondly, a simple example with analytical solution is given to verify the model; finally, two hydraulic fracturing problems using different viscosities are studied to examine the influence of pore pressure and fluid viscosity on hydraulic fracturing.

2. Basic assumptions

As shown in Fig. 1, triangular solid elements adjoined through joint elements are used to represent the rock in FDEM,[50–52] with the assumption that the solid elements are impervious and all joint elements are allowed bi-directional flow by fluid. Besides an initial aperture a_0 of joint elements is given to represent the permeability of rock matrix.

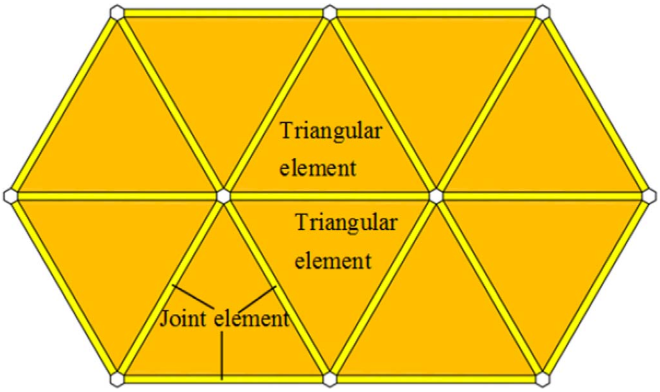

Fig. 1. Connection of triangular elements and joint elements.

When some joint elements break (i.e. new cracks generated), the aperture of those joint elements increases resulting in an increased permeability. As a consequence, both seepage in fracture and porous media flow in rock matrix can be characterised.

3. Considerations of rock permeability in FDEM-flow

Based on the above assumptions, we will see that problems of both porous media flow and fracture seepage can be reduced to pure fracture seepage problems. The hydro-mechanical model includes the following process: fluid flow through a crack applies pressure to the two walls of the crack, resulting in opening or closing under the action thereof. However, opening or closing of the crack will affect the fluid flow in the crack and lead to a fluid pressure change.

As shown in Fig. 2(a), fluid in the crack applies fluid pressure onto its two walls. Under the action of fluid pressure, the crack aperture might increase if the fluid pressure is large enough (see Fig. 2(b)). According to the cubic law, i.e. the flow rate is proportional to the cube of the aperture, crack opening affects the flow rate and fluid pressure in turn.

Since joint elements are inserted in the common edge of each triangular element in FDEM, triangle solid elements and joint elements form a topology as shown in Fig. 3. Only the joint elements sustain fluid flow, and all joint elements will be involved in the seepage calculation. In Fig. 3, a white node denotes an intersection of the fluid flow network paths, and also an intersection of joint elements and triangular elements. A segment (i.e. a joint element) between any two adjacent white nodes constitutes a flow path, such as the path connecting Nodes 4 and 2. While all the joint elements in one dashed circle with a node as the centre constitutes the node control volume. The control volume of a node is constituted by all the joint elements in one dashed circle surrounding the node. In the seepage calculation, the fluid pressure at a node will represent the fluid pressure of the dashed circle.

The procedure to solve the flow rate between the two nodes is explained below. The pressure difference between two nodes is first calculated. Take Node 2 in Fig. 3 as an example. The total pressure difference between Node 2 and Node 1 is given by

$$\Delta p = p_2 - p_1 + \rho_w g(y_2 - y_1), \tag{1}$$

where ρ_w is density of fluid, p_1 and p_2 are fluid pressure at Nodes 1 and 2, and y_1 and y_2 are the vertical coordinates of Nodes 1 and 2, respectively.

Using the cubic law, the flow rate from Node 1 to Node 2 is calculated as

$$q_{21} = -\frac{1}{12\mu}a^3\frac{\Delta p}{L}, \tag{2}$$

where, a is the average aperture of the joint element, μ is the fluid viscosity, and L is the length of the joint element. The introduction of the negative sign is due to the convention that flow-out is negative and flow-in is positive.

The average aperture a is not constant, which depends on the average normal displacement of the joint element as illustrated in Fig. 4(a). The average aperture of the joint elements is expressed as

$$a = a_0 + u_n, \tag{3}$$

where a_0 represents the initial aperture of the joint element, and u_n is the average normal displacement of the joint element